Combustion and Flame 193 (2018) 218–228

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Characterization of stratified fuel distribution and charge mixing in a DISI engine using Rayleigh scattering

Stina Hemdal[1]

Volvo Group Trucks Technology, SE-417 15 Gothenburg, Sweden

ARTICLE INFO

Article history:
Received 11 March 2018
Revised 14 March 2018
Accepted 15 March 2018

Keywords:
Gasoline direct-injection
Stratified
Imaging
Rayleigh scattering
Charge-mixing

ABSTRACT

The stratified fuel distribution and early flame development in a firing spray-guided direct-injection spark-ignition (DISI) engine were characterized applying optical diagnostics. The objectives were to compare effects of single and double injections on the stratified air–fuel mixing and early flame development. Vaporized in-cylinder fuel distributions resulting from both single and double injections before, during and after ignition were selectively visualized applying Rayleigh scattering. The optical investigation of the in-cylinder fuel distributions and early flame propagation corroborated the better mixing, showing that double injections were associated with more evenly distributed fuel, fewer local areas with high fuel concentrations, faster initial flame spread and more even flame propagation (more circular flame spreading). The results support the hypothesis that delivering fuel in closely coupled double injections results in better mixing than corresponding single injections. The improved mixing is believed to stem from the longer time available for mixing of the air and fuel in double injection events.

1. Introduction

Spray-guided (SG) stratified-charge combustion is an interesting concept since it has proven potential to greatly reduce fuel consumption (by up to around 20% [1,3] compared to homogenous stoichiometric operation) Nevertheless, it is somewhat of a niche technology in direct-injection spark-ignited (DISI) engines due to challenges in maintaining stable combustion and sufficiently limiting engine-out emissions. Most efforts to develop DISI engines are focused on stoichiometric or diluted homogenous combustion in combination with downsizing and boosting [1,2]. However, spray-guided stratified-charge operation offers greater dilution at low and medium loads, not accessible in homogenous charge operation, and thus fuel economy benefits. This is because in stratified mode the ignitable fuel–air mixture is concentrated around the spark plug, which allows operation with wide open throttle.

The benefits and drawbacks of stratified combustion have been described in many publications, including several good reviews [1–3]. The efficiency gains (increases in specific heat ratios with reductions in pumping losses and heat losses to the walls), and hence improvements in fuel consumption, are mainly due to the high dilution. The main drawbacks are reductions in combustion stability and increases in engine-out particle emissions.

In stratified operation, the fuel is injected late during the compression stroke, forming a fuel cloud that is confined to the center of the cylinder volume. This enables high dilution, and thus globally lean conditions, by creating an ignitable mixture at the spark location and time. Ignition occurs at or shortly after end of injection, so there is limited time for the air and fuel to mix, resulting in uneven distributions of the fuel. Particle formation is promoted by locally rich zones [4], and thus by the inhomogeneity of the fuel distribution.

Uneven distributions of fuel are also believed to cause cycle-to-cycle variation, through irregular flame propagation. Extending the time between end of injection and ignition increases the time available for mixing, but also rapidly leads to poorer flame propagation, reductions in combustion stability and ignition failure since the mixture spreads excessively, becomes too lean and is no longer ignitable [5]. The challenge is to enable sufficient mixing while avoiding overmixing and hence over-leaning and loss of ignitability.

The ignition and early flame propagation in stratified combustion are influenced by various factors, but mainly by the fuel distribution and mixing, together with the in-cylinder turbulent flow field [6]. Ignitable mixtures may be located in regions where the local turbulence intensity is too high for reliable ignition and flame propagation [7]. Local flow field fluctuations may also impede the motion of the spark and early flame kernel towards the main stratified fuel cloud, which has been identified as a significant factor in combustion instability [8,9].

E-mail addresses: stina.hemdal@volvo.com, hemdal@chalmers.se

[1] Mechanics and Maritime Sciences, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden

https://doi.org/10.1016/j.combustflame.2018.03.020
0010-2180/

While most research on DISI combustion has concerned systems with multi-hole injectors, piezo-actuated outward-opening injectors are used in most spray-guided stratified charge engines that have entered production. These injectors enable precise deliveries of small amounts of fuel, and hence multiple injections separated by short delay times. Split-injection strategies, where the fuel is delivered in two or several short pulses, have been pursued and shown to give higher indicated mean efficient pressure (IMEP) (at constant fuel mass), larger ignition windows, higher combustion stability and lower engine-out emissions [10–12]. Hence, it has been hypothesized that a split injection strategy can improve combustion efficiency. Split injections have proven to reduce spray penetration, and thus fuel impingement on the piston crown [10,12]. Furthermore, a split injection strategy reportedly results in less in-cylinder soot formation, mostly due to the lower impingement on the piston crown, and hence lower probabilities of piston pool fires [13]. Split injections may also enable better containment of the fuel vapor in the center (within the piston bowl) and creation of a favorable flow field that directs the burning mixture towards the remaining fuel.

Many detailed studies of fuel injection have examined phenomena in spray vessels with constant pressure, temperature and volume. Such studies provide valuable information about spray behavior. However, they provide limited information about the resulting fuel distributions and mixing processes in revolving and firing engines, which have been examined to some extent (as outlined in the following section), but far less extensively, especially in engines using spray-guided systems with outward-opening injectors. The study reported here addressed some of this research gap by acquiring detailed in-cylinder images of fuel distributions in a firing SGDI SI engine. The images (and inferred information) may assist model validation, engine design and combustion optimization.

1.1. Study

The objectives of the study were: to characterize the stratified fuel distribution in a firing SGDI SI engine, and compare effects of single and double injections on the stratified air–fuel mixing and early flame development, thereby determining if and why split injections can improve mixing and combustion efficiency. Additionally to assess Rayleigh scattering as a method to visualize the vaporized fuel distribution in a gasoline direct injection engine operated in stratified mode. Therefore, vaporized in-cylinder fuel distributions resulting from both single and double injections before, during and after ignition were visualized. In contrast to various other studies of in-cylinder fuel distributions, distributions of both liquid and vaporized fuel were captured by analysis of laser-induced fluorescence (LIF) of diacetyl (10% v/v) [14] added to the fuel and Rayleigh scattering. The images also captured flame initiation and early propagation.

The hypothesis was that injecting the fuel as a closely coupled double injection can improve mixing, thereby resulting in a more even distribution with less steep fuel concentration gradients.

Analysis of the in-cylinder flow field was beyond the scope of the presented experimental work, but it still provides potentially valuable information about the fuel distribution (liquid and vaporized) and mixing process in a firing engine. The novel and probably most important features of the study are the Rayleigh scattering-based imaging and characterization of the vaporized fuel distributions in a firing SGDI SI engine with an outward-opening injector.

1.2. Rayleigh scattering

Rayleigh scattering is the elastic scattering of light by molecules and particles much smaller than the wavelength of the light. In an engine, planar laser Rayleigh scattering can be applied to obtain images of the vaporized fuel. The intensity of the Rayleigh-scattering signal is directly proportional to the laser intensity, the number density of the molecules and the Rayleigh cross-section, so quantitative measurements can be relatively easily acquired. However, the incident light and signal have the same wavelength, so scattered light from other sources can strongly interfere with measurements. This a major challenge when applying Rayleigh scattering in optical engines because scattering in the entrance windows and reflections on the cylinder walls will enhance the background noise. Interference by liquid droplets in the combustion chamber is also highly problematic, as Mie scattering is orders of magnitude stronger than Rayleigh scattering, and thus readily drowns Rayleigh signals. Thus, to get good images of the vaporized fuel ideally no liquid fuel should be present, and both reflections and interference from droplets should be avoided to obtain sufficiently high Rayleigh scattering signal-to-noise ratios in engine research.

Images of the fuel distribution in port-fueled SI engines have been acquired by Rayleigh scattering analysis [15–17], for example to investigate mixture variations and quantitatively analyze air-fuel distributions [17]. It has also been used to map temperature fields, in conjunction with LIF measurements of NO, in an optical SI engine [18]. In addition, it has been successfully applied for quantitative visualization of the vaporized fuel outside the liquid core of Diesel jets [19,20] and to study the mixing process in Diesel fuel sprays [21,22]. However, it has not been previously used in any published investigation (to our knowledge) for the purposes of this study, as described in the previous section.

Table 1
Fixed engine parameters.

Bore	83 mm
Stroke	90 mm
TDC volume	53 cm^3
Displacement volume	488 cm^3
Compression ratio	10.1
IVO/IVC	340/-120 CAD aTDC
EVO/EVC	105/-355 CAD aTDC

2. Experimental procedure

2.1. Engine and operation conditions

The engine used in the reported experiments was a single-cylinder engine (AVL 5411.018) with optical access through the piston crown, the upper part of the cylinder liner and the pent roof. The engine was equipped with an elongated piston with a flat quartz plate as the piston crown (diameter of 63 mm), which provided a view into the cylinder from below via a piston mirror inclined under the piston crown (Bowditch design). The single-cylinder engine is schematically illustrated to the left in Fig. 1, and an image of the cylinder head (showing positions of the intake valves, exhaust valves, injector tip and spark plug), as viewed through the optical piston, is presented in Fig. 2. The fixed engine parameters are given in Table 1. For the direct injection of the fuel, a Bosch outward-opening piezo-actuated injector was mounted in the combustion chamber roof. The injector and a BMW triple electrode spark plug were centrally mounted in a closely coupled configuration along a line between the intake and exhaust valves (Fig. 3). The injector was inclined by 20° and the spark plug by 10° relative to the vertical axis. A Haskel pump was used to deliver fuel (isooctane with 10%, v/v, of diacetyl added as a tracer for LIF measurements) at a pressure of 200 bar. The engine speed was kept constant at 1500 rpm (at which one crank angle degree, CAD, corresponds to 111 µs) using a dynamometer connected to the engine crank shaft. The optically accessible engine was operated in